Cavitation Within Fuel Injectors: Development and Multiscale Validation of Euler-Lagrange based Computational Methods for Modeling Cavitation within Fuel Injectors

Project ID: ACS104

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BOSTON UNIVERSITY

JUNE 7, 2017

Overview

Timeline

- Project start date: 2/01/2016
- Project end date: 1/31/2019
- Percent complete: 36%

Barriers

- Barriers addressed
  - Lack of fundamental knowledge of advanced engine combustion regimes
  - Lack of modeling capability for combustion and emission control

Budget

- Total project funding
  - DOE share: $543,074
  - Contractor share: $200,000
- Funding received in FY 2016: $180,989
- Funding for FY 2017: $180,989

Partners

- Boston University – Lead
- Oak Ridge National Laboratory

Objectives and Relevance

Overall Objective

- To develop and validate more accurate, physics-based, mathematical submodels for use in standard multiphase CFD software to enable better prediction of cavitation within fuel injectors.

Objectives this period

- Select appropriate open source Lagrangian code for cavitation simulations
- Construct small scale experimental setup of cavitation in a canonical nozzle
- Image cavitation in real fuel injector using the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL).

Impact

- Computational models will allow more detailed studies of cavitation within fuel injectors
- Small scale experiments will provide insight into conditions causing cavitation
- Small scale experiments and HIFR data provide validation data to ensure accurate simulations

Milestones

Milestone and Go/No-Go Decision Points	Planned Date
Microscale experiments required for SPH development completed	August 30, 2017
Second measurement campaign completed	November 30, 2017
Significant population of cavitation database, so upscaling can begin.	June 30, 2017
First results from upscaling obtained	August 30, 2017
Go/No-Go: Simulation of bubble dynamics with the SPH method, as evidenced by initial validation results	January 31, 2018

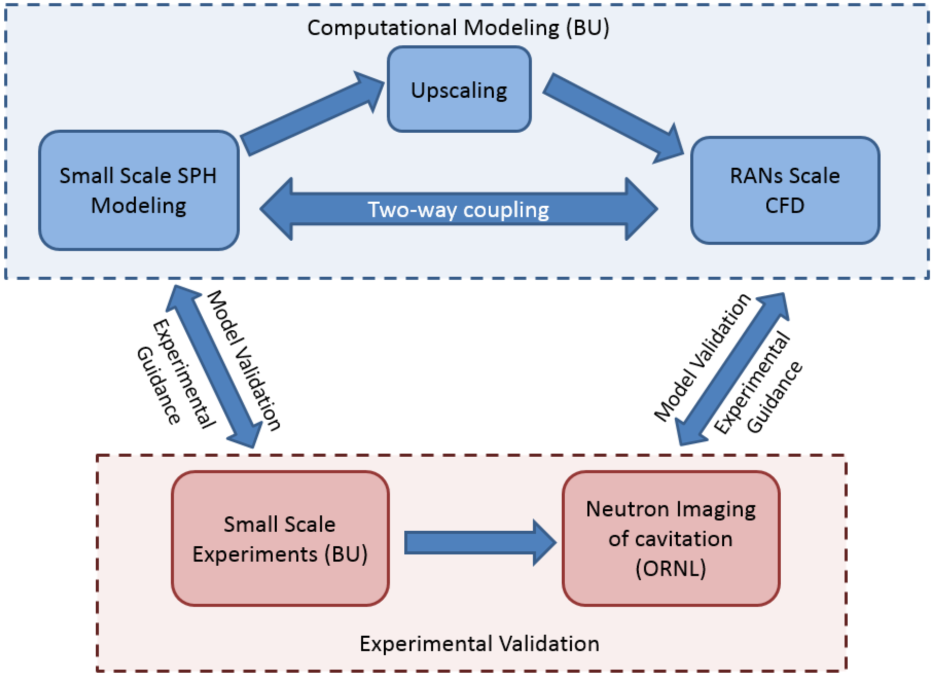
Technical Approach

Computational Development

- Lagrangian particle based model of bubble dynamics
- Coupling of Lagrangian model to RANS CFD

Experimental Characterization and Validation

- Small-scale experiments in idealized fuel injector
- Neutron imaging of cavitation in real fuel injector



Technical Accomplishments: Smoothed Particle Hydrodynamics Simulations of Multiphase Flow

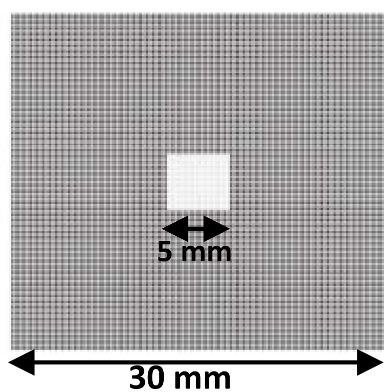
Goal: Simulate bubble behavior inside fuel injector nozzle

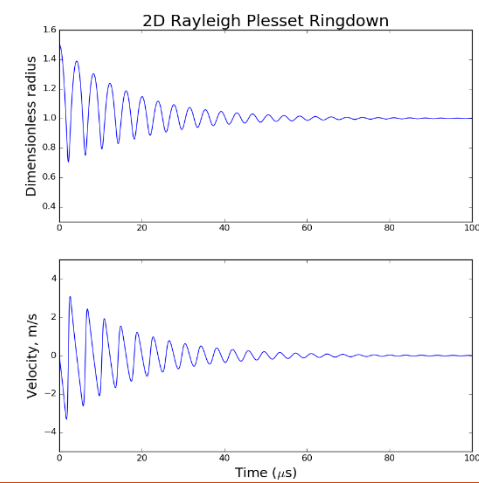
Initial work focuses on inclusion of appropriate sub-models for surface tension, pressure, etc. and validation of bubble dynamics

Validation cases:

- Consider cases for air bubble in water or water droplet in air (ρ_w/ρ_a = 1000)
- Simulations of gas bubble and liquid droplet shape oscillations
- Rayleigh – Plesset solution for bubble dynamics

$$\tau = 2\pi\sqrt{\frac{\rho R^3}{\sigma(n^3-n)}}$$



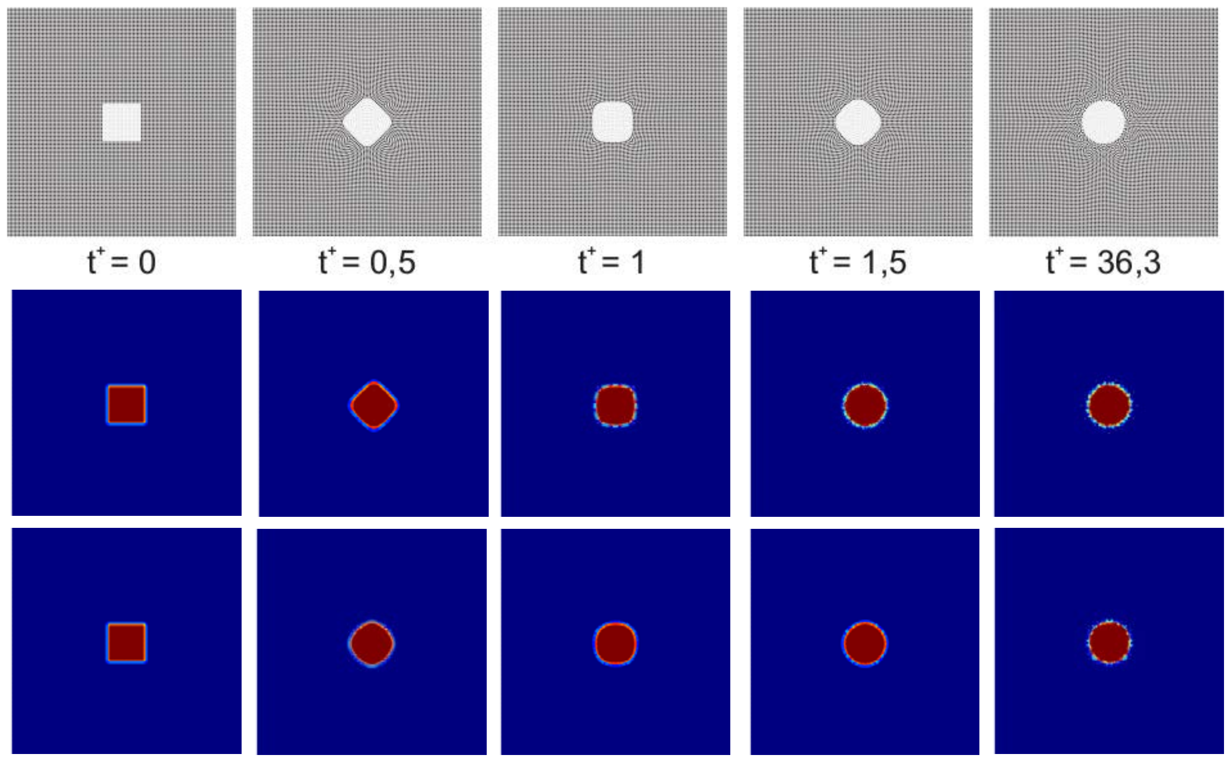


Technical Accomplishments:
Liquid Droplet and Gas Bubble Shape Oscillations

Liquid Droplet from Literature

Liquid Droplet

Gas Bubble

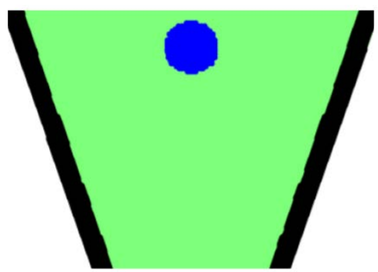


Technical Accomplishments:
On Going SPH Bubble Modeling

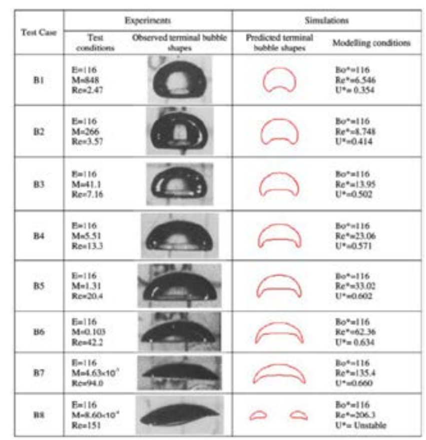
Focusing on single bubble dynamics before moving to multiple bubbles

Incorporating bubble dynamics into nozzle simulation

Next steps inclusion of wall effects, multi bubble dyanmics



Hua et al 2007



Test Case	Experiments: Test conditions	Experiments: Observed terminal bubble shapes	Simulations: Predicted terminal bubble shapes	Simulations: Modelling conditions
B1	E=116 M=848 Re=2.47			Bo*=116 Re*=6.546 U*= 0.354
B2	E=116 M=266 Re=3.57			Bo*=116 Re*=8.748 U*=0.414
B3	E=116 M=41.1 Re=7.16			Bo*=116 Re*=13.95 U*=0.502
B4	E=116 M=5.51 Re=13.3			Bo*=116 Re*=23.06 U*=0.571
B5	E=116 M=1.31 Re=20.4			Bo*=116 Re*=33.02 U*=0.602
B6	E=116 M=0.103 Re=42.2			Bo*=116 Re*=62.36 U*= 0.634
B7	E=116 M=4.63×10[illegible] Re=94.0			Bo*=116 Re*=135.4 U*=0.660
B8	E=116 M=8.60×10[illegible] Re=151			Bo*=116 Re*=206.3 U*= Unstable

Technical Accomplishments: RANS Scale Simulations of Cavitation in a Nozzle

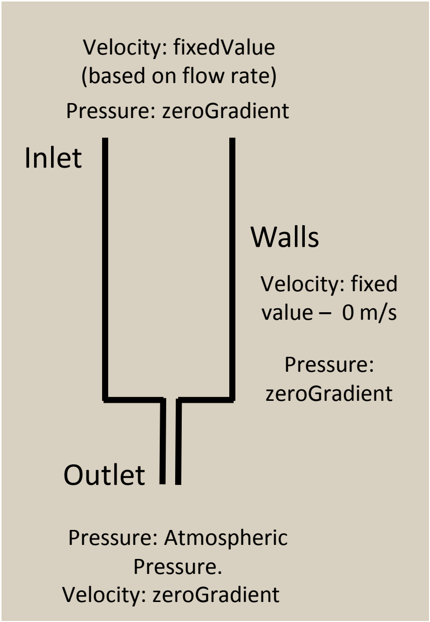
Goals:

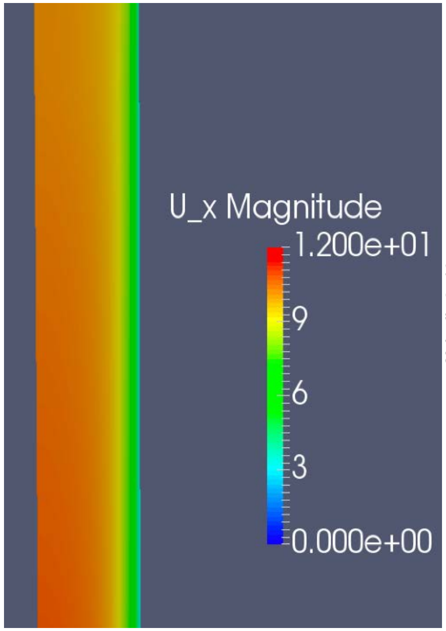
- Investigate flow field in nozzle being tested at BU
- Gain better knowledge about current use of sub-models using homogenous volume fraction methods
- Utilize front tracking based volume of fluid (VOF) methods already in OpenFOAM

simpleFOAM:
steady state solver in OpenFOAM for incompressible flows with turbulence modelling. kEpsilon turbulence model used in simulations.

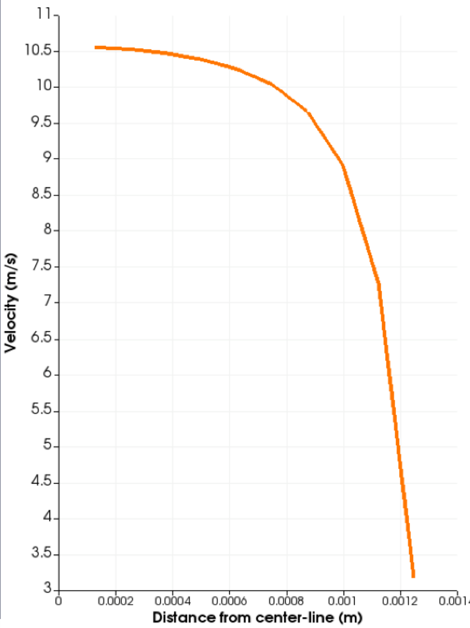
Non-Cavitating Case

Upstream Flowrate: 2.68 lpm





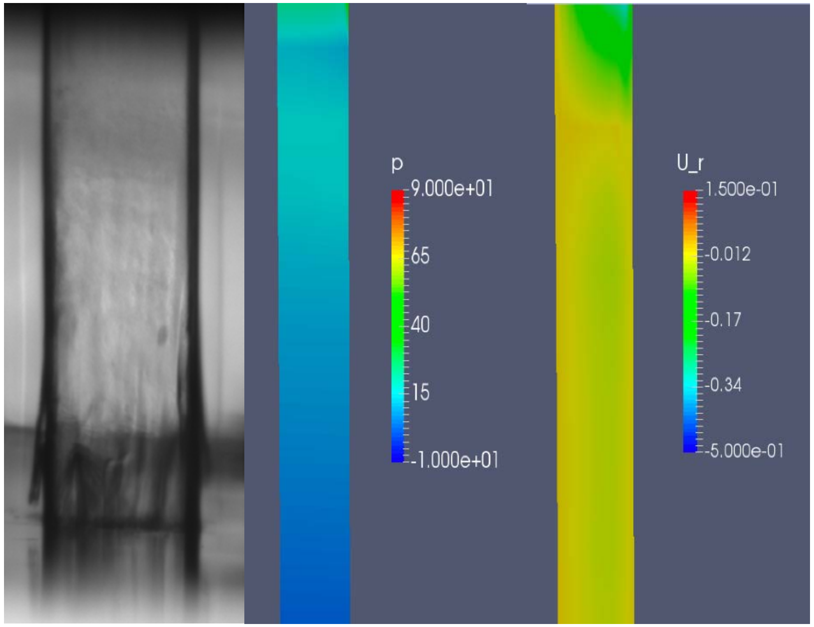
Velocity Profile in Nozzle Section



*velocities in m/s

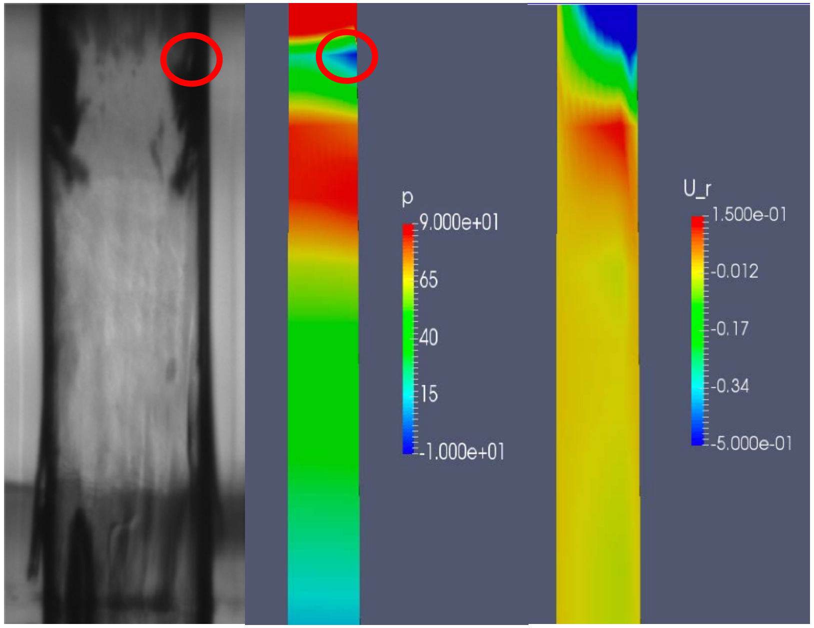
Technical Accomplishments: RANS CFD Results

Non-Cavitating Case



OpenFOAM simulations are shown from 0 to R (model only half of experimental picture)

Cavitating Case



Low-Pressure is indication of cavitation in simulations. Cavitation is also seen at a point near the top of the nozzle in the experiments

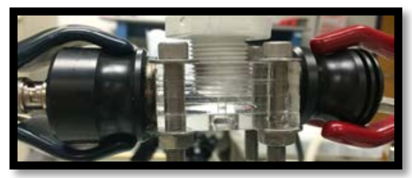
*velocities in m/s

Technical Accomplishments: Developed Acoustical Experimental Setup for Small Scale Experiments

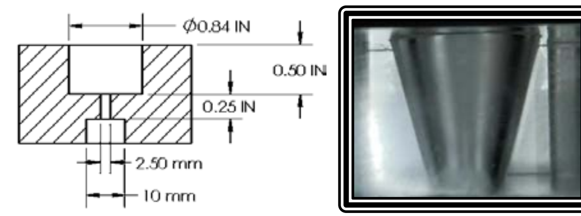
Conduct baseline flow cavitation experiments for comparison and validation of computations

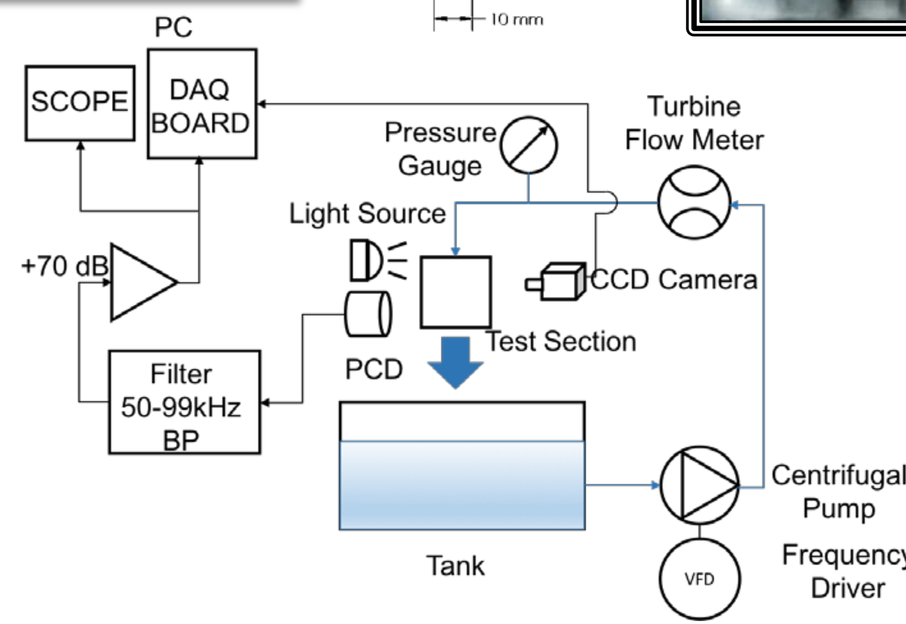
- Acoustic diagnostic
- Optical diagnostic
- Flow variables:
  - Flow rate
  - Nozzle size
  - Nozzle geometry
- Material variables
  - Dissolved gas
  - Cavitation nuclei
    - Clean (Filtered 200nm)
    - Particulates
    - Microbubbles

Replaceable test section with acoustic transducers



Example test section geometries



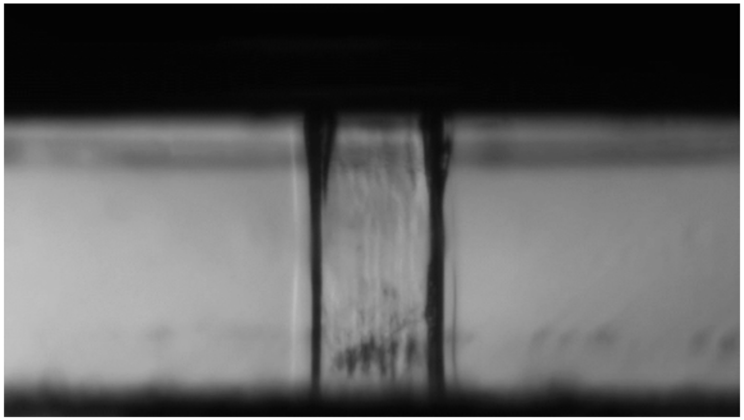


Technical Accomplishments:
Stepped 2mm orifice results near onset

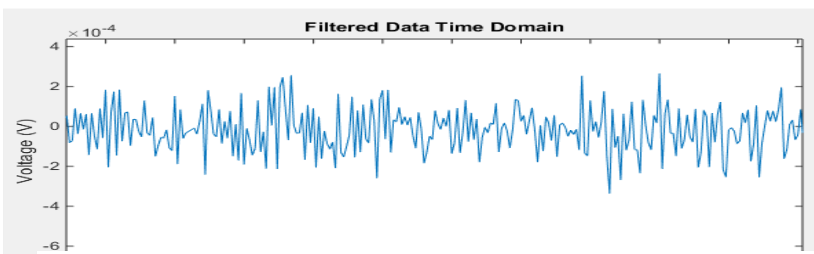
Q = 43 mL/s *No cavitation*

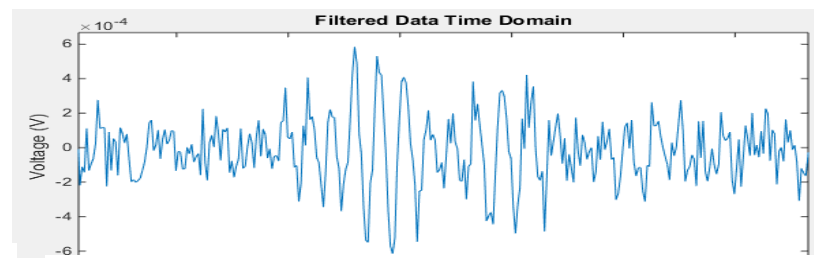
Q = 68 mL/s *Cavitation*

HS and normal imaging

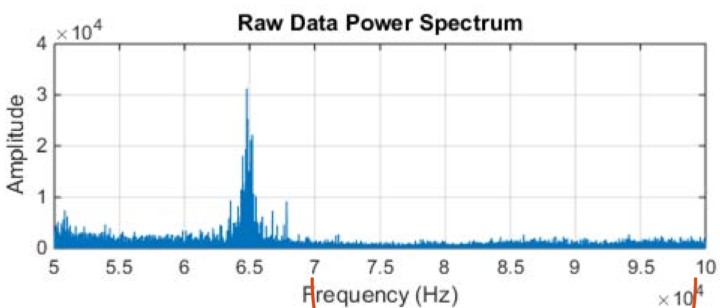


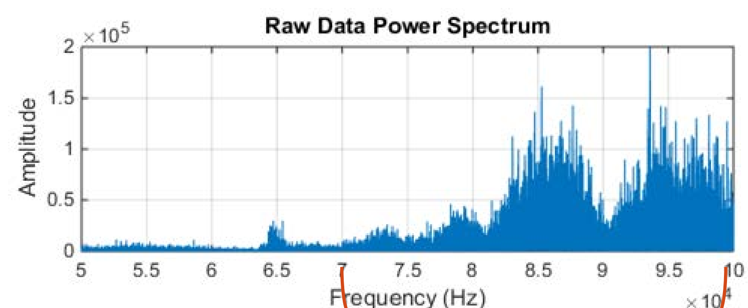
Acoustic time series





Acoustic spectral domain





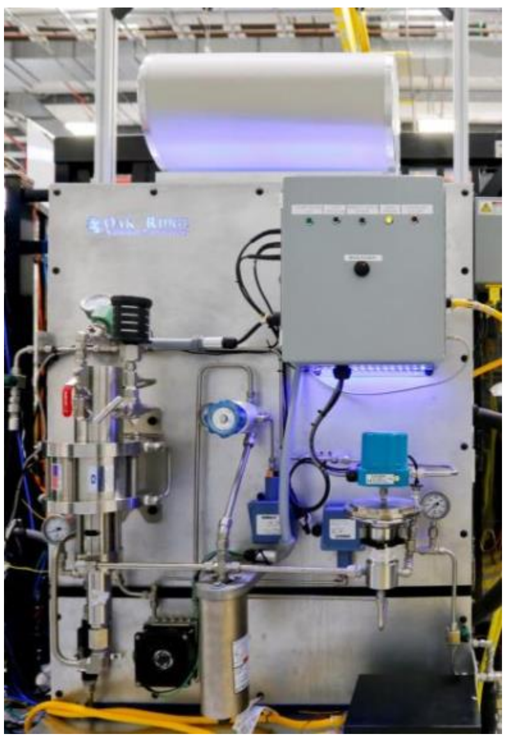
Detection band

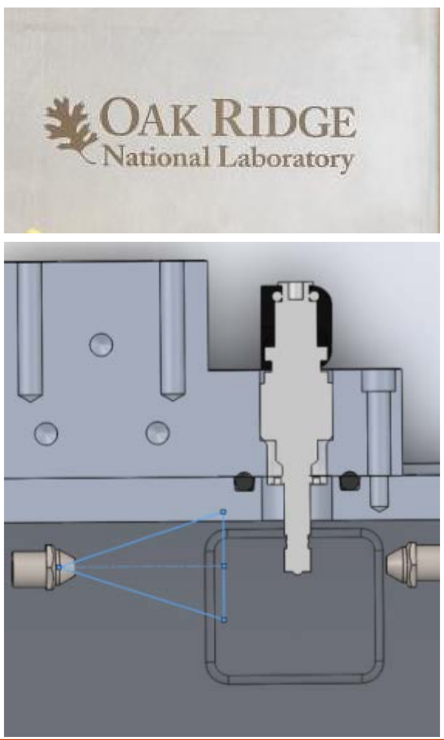
Detection band

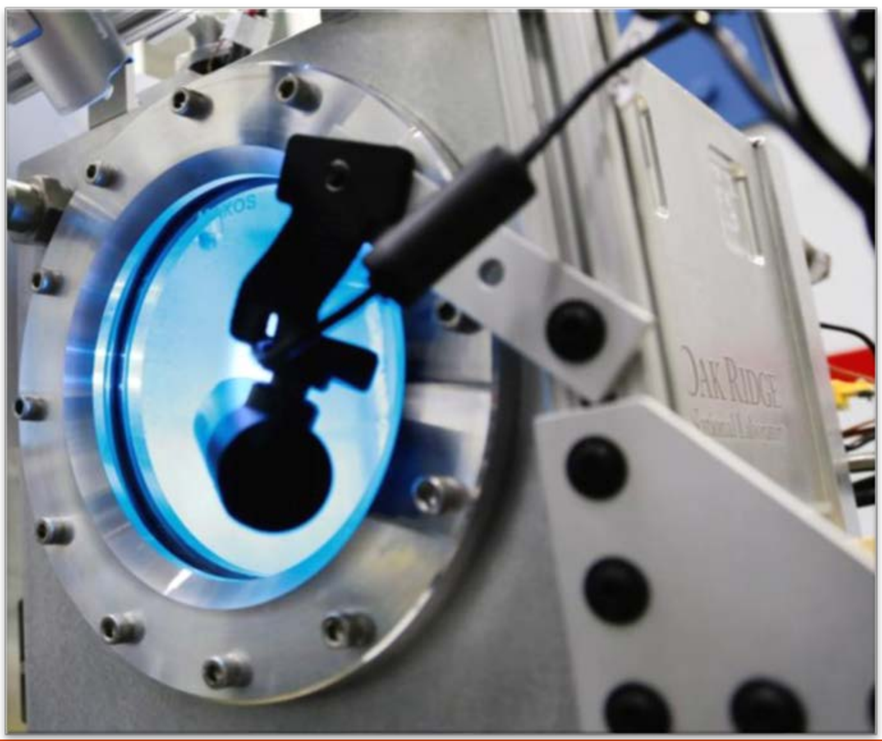
Technical Accomplishments: Imaging of fuel inject with ORNL High Flux Isotope Reactor (HFIR)

Spray chamber designed to allow for high sweep gas flow, sub-ambient P and elevated temperature

- Multiple cartridge heaters for fuel injector and chamber temperature control (>100°C)
- Wide pressure range: 0.01 to 3-4 bar absolute (next generation target 6 bar)
- Direct heated sweep gas with high flowrate pumping system







Technical Accomplishments: Campaign performed at conditions to minimize fogging and encourage flash evaporation

Single hole injector from GM

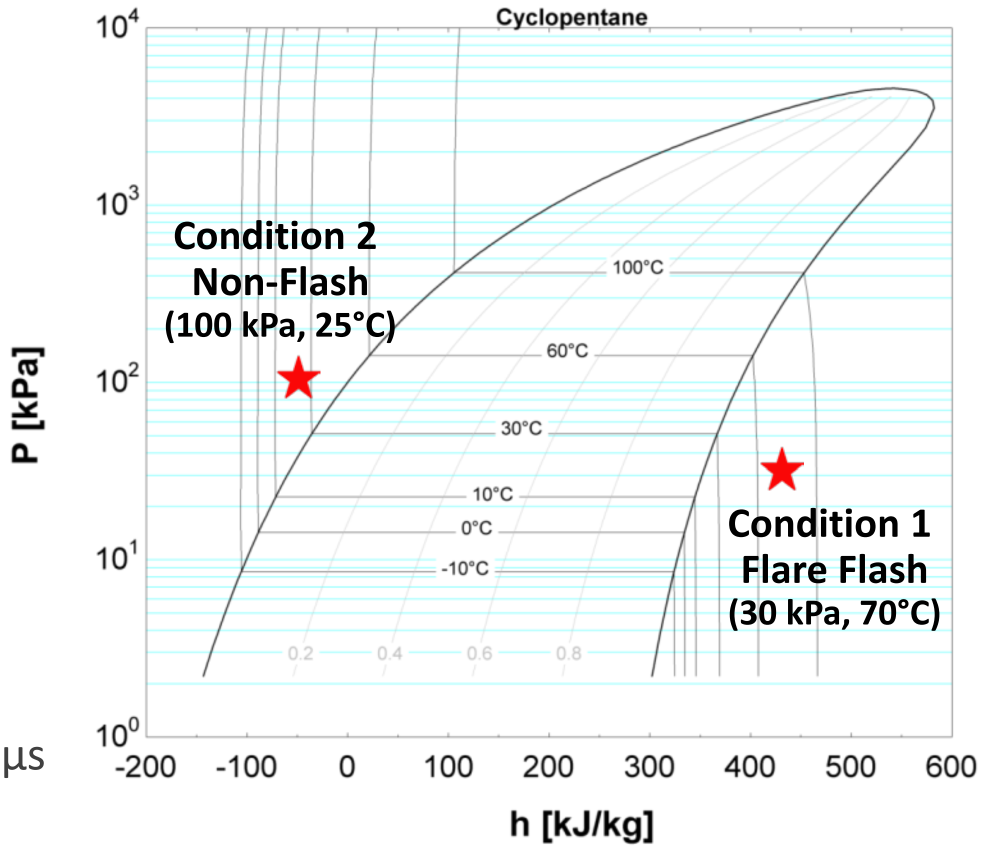
- Ron Grover and Scott Parrish

Fluid is cyclopentane

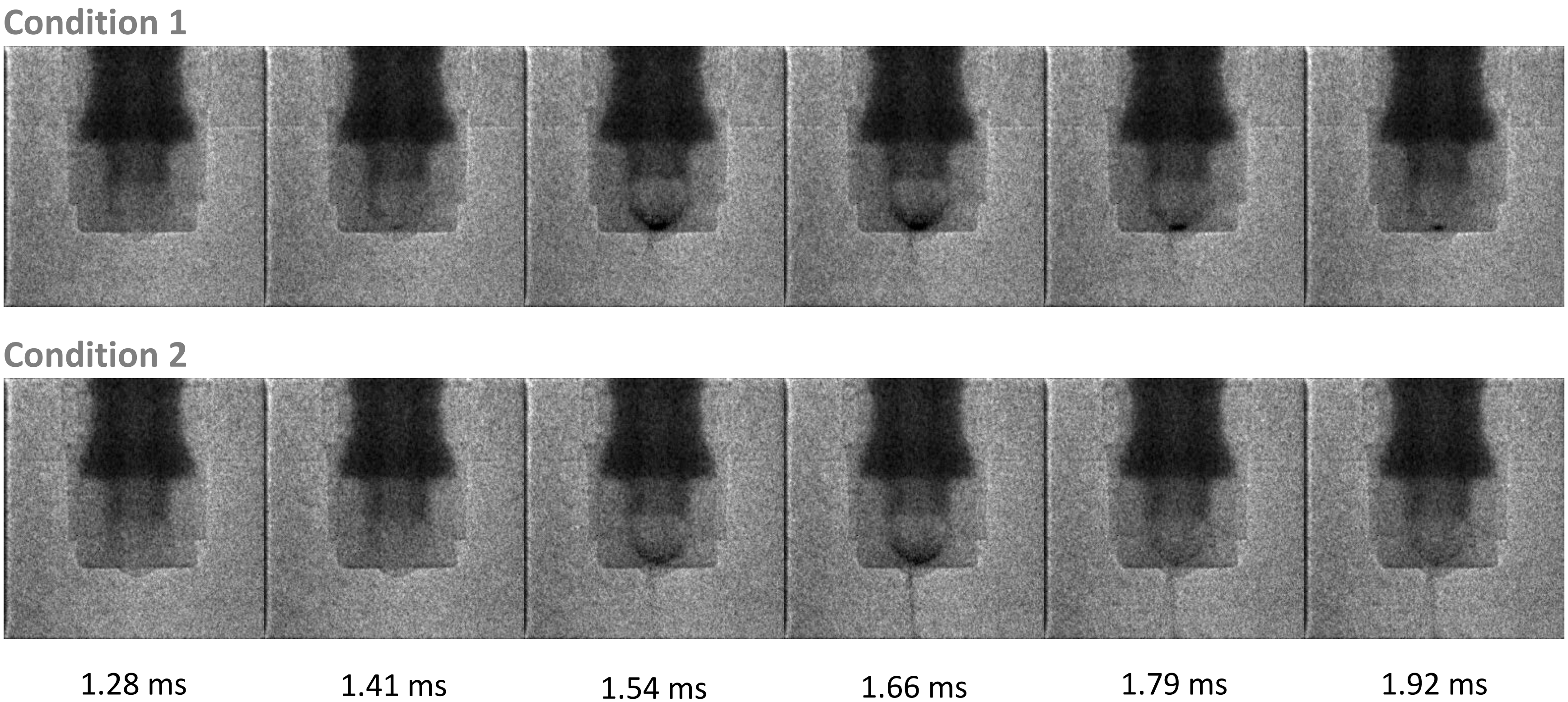
- Flash boils near ambient

Injection timing for composite image:

- 0.367 ms injection
- 25 Hz
- 20 µs resolution
  - ~19 frames during injection
  - 1 ms before, ~5 ms after injection recorded
- ~40 s of neutron exposure for each 20 µs frame over 20-24 hours
  - ~2M injections

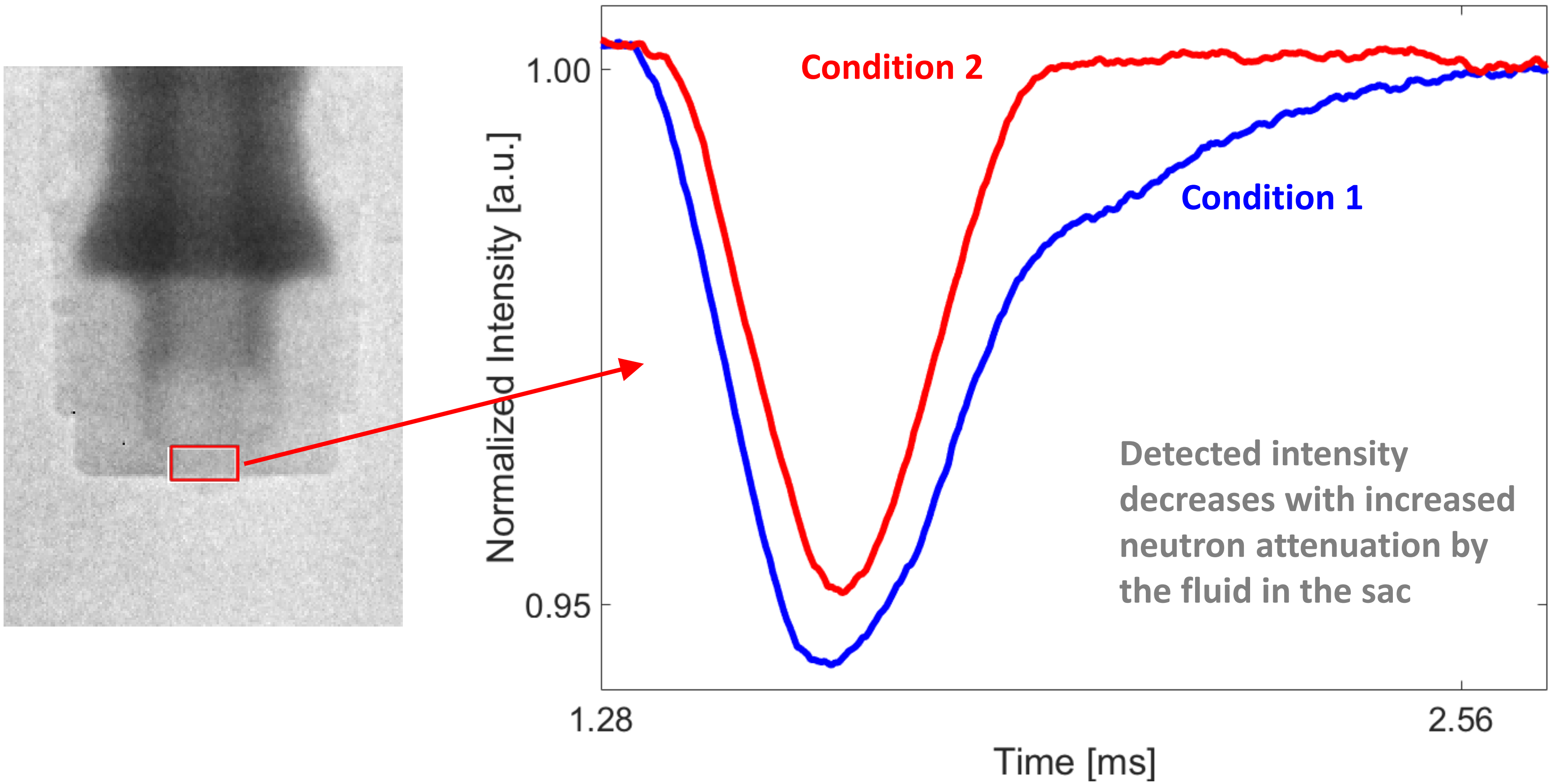


Technical Accomplishments:
Fluid behavior at the two conditions differ discernibly



More neutron attenuation by the fluid is measured in the sac in Condition 1 (flash), and more in the spray in Condition 2 (non-flash).

Technical Accomplishments: Sac emptying rates differ with condition



Condition 1 (Flash): More neutron attenuation by the fluid is measured, and the sac takes longer to empty.

Condition 2 (Non-Flash): Less neutron attenuation by the fluid is measured, and the sac empties very quickly.

Responses to Previous Year Reviewers' Comments

- New project
- Not reviewed last year

Collaborations

Boston University – Developing computational models of cavitation in fuel injectors and small scale experiments of idealized fuel injector

Oak Ridge National Laboratory – Experimental data of cavitation in a real fuel injector through imaging at operating conditions using the ORNL HFIR

Remaining Challenges and Barriers

Large parameter ratios between phases makes achieving numerical and interfacial stability with physical values challenging in small scale modeling.

Resolution of HFIR images limits details that can be seen in real fuel injector.

We need accurate computation of Eulerian flow to get local pressure threshold of cavitation.

We need experiments with controlled nuclei size and concentration to understand causes of cavitation onset.

We need to quantify spatial distributions of type of cavitation:

- High-speed imaging
- Passive Cavitation Mapping (PCM)

Proposed Future Work

On Going

- Small scale experiments at various operating conditions to understand the conditions that initiate cavitation
- Implementation and testing of RANS cavitation model based on OpenFOAM and built-in submodels
- Continued development and validation of small scale cavitation model

Planned

- Second imaging campaign with the ORNL HFIR. A proposal has been submitted for beam time on the ORNL HFIR to image the fuel injector under operating conditions that are expected to induce cavitation
- Joint BU-ORNL acoustic experiments on ORNL fuel injector assembly (not in HFIR beam) to use BU laser vibrometer to measure acoustics to directly compare with neutron imaging (May 2017)
- Control cavitation by controlling nucleation for purposes of mitigating cavitation damage and producing desired nozzle exit spray characteristics

Any proposed future work is subject to change based on funding levels.

Summary

Initial SPH model development included the addition of multiphase physics to an existing free surface flow SPH code and initial validation of bubble dynamics.

- Considering bubble dynamics under realistic densities, bubble shape and equilibrium
- Implementing model in conical nozzle for comparison to experimental data
- Developing RANS CFD model for larger nozzle simulation

Baseline experimental system developed which demonstrates capability of providing canonical data for comparison with computational results.

Successful imaging campaign of a real fuel injector using the HFIR at ORNL

- 96 continuous hours of experiment
- 2 spray conditions using cyclopentane – flash and non-flash
- Initial data analysis shows intriguing results between two injection conditions
- ORNL CT scan data of fuel injector transferred to BU for solid-modeling analysis

Acknowledgement

- This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) and the Department of Defense, Tank and Automotive Research, Development, and Engineering Center (TARDEC), under Award Number DE-EE0007332."

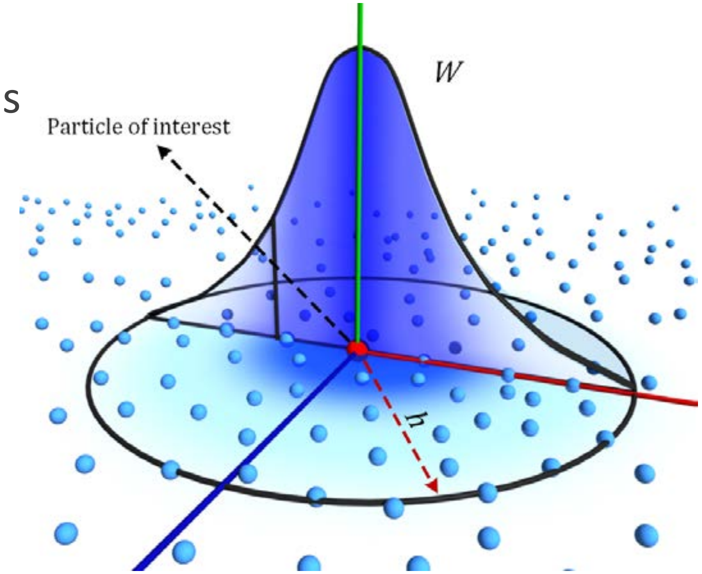
Technical Backup Slides

SPH Formulation

Smoothing function is used to approximate the governing equations

$$A_s(\vec{x}) = \int A(\vec{x}')W(\vec{x}-\vec{x}',h)d\vec{x}'$$

Simulation domain is divided into discrete particles



$$A_s(\vec{x}) = \sum_i \frac{A_i}{n_i} W(\vec{r}_{ij},h)$$

Momentum Conservation (Navier-Stokes)

$$\rho\frac{D\vec{v}}{Dt} = -\nabla P + \mu\nabla^2\vec{v} + \rho\vec{g}$$

$$\frac{D\vec{v}_i}{Dt} = -\frac{1}{m_i}\sum_{j\in fluid+solid}\left(\frac{P_j}{n_j^2}+\frac{P_i}{n_i^2}\right)\nabla_i W(\vec{r}_{ij},h) + \frac{1}{m_i}\sum_{j\in fluid+solid}\frac{(\mu_i+\mu_j)\vec{v}_{ij}}{n_i n_j}\frac{\vec{r}_{ij}}{\vec{r}_{ij}^{\,2}}\cdot\nabla_i W(\vec{r}_{ij},h) + F_i^{ext}$$

Sampath, Ramprasad, et al. (2016)

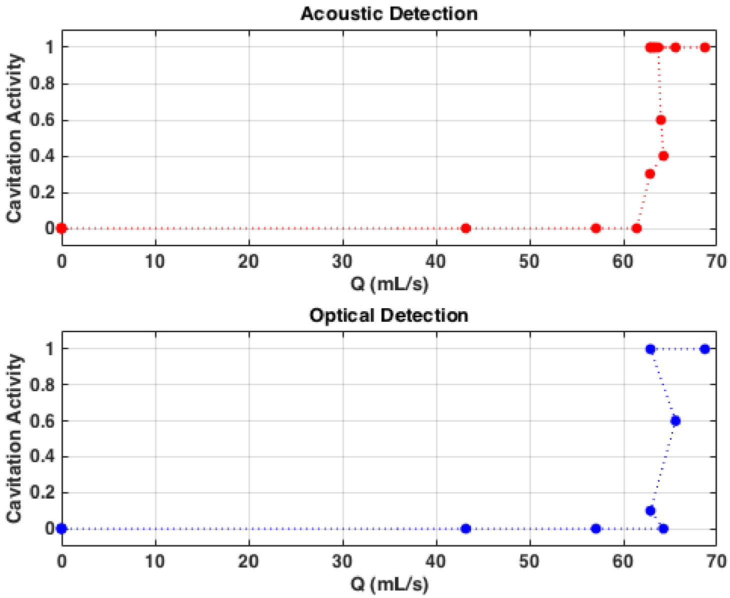
Code validation from experimental results

Experiments tell us:

1. Onset threshold
2. Nuclei type, size, concentration
3. ‘Sheet’ threshold
4. Inertial cavitation at onset, sheet cavitation as flow increases

Computation must:

1. Incorporate a cavitation inception criterion which agrees with experimental onset
2. Exhibit same nuclei parameter variation
3. Transition to coherent sheet structures at same flow rates
4. Yield inertial collapses for onset parameters

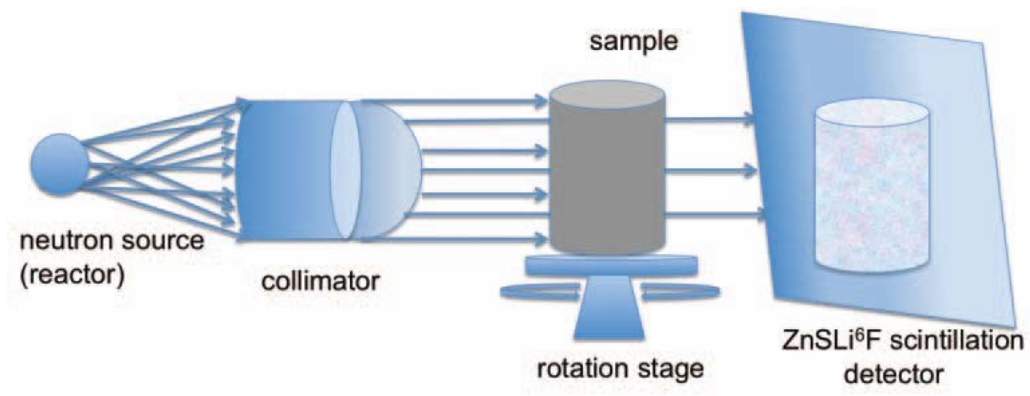


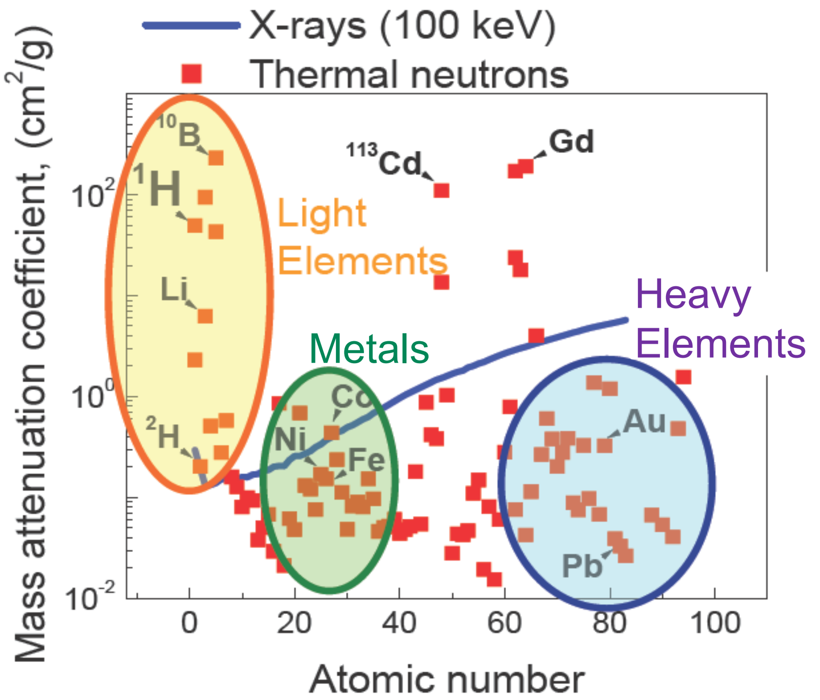
Neutrons can penetrate metals while still strongly interacting with light elements

Neutrons are heavily attenuated by some light elements (^{1}H, ^{10}B, et)

- Can penetrate metals with minimal interactions
- Highly sensitive to water and hydrocarbons/fuel
- Image is based on absence of neutrons

X-ray absorption increases for heavy/dense elements





Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

Neutron imaging is a complementary analytical tool

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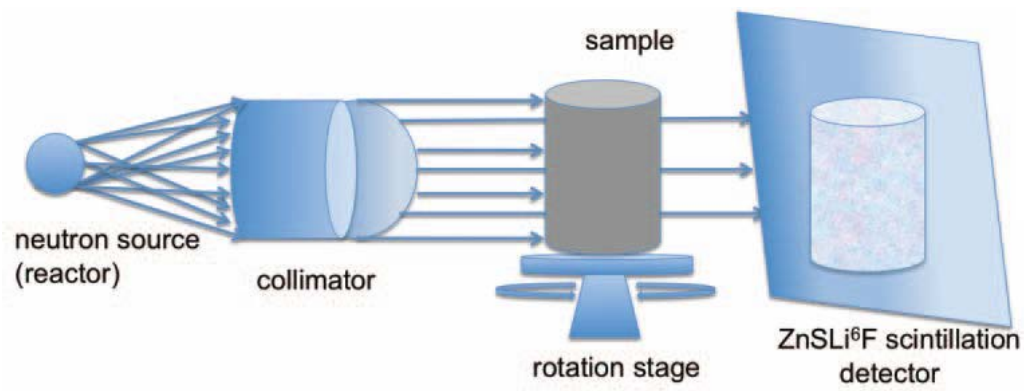

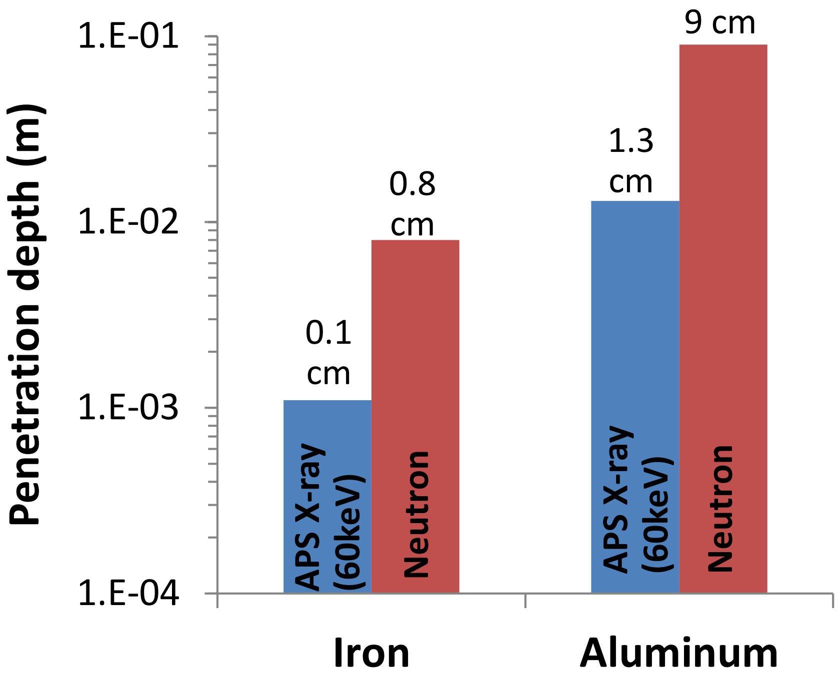

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http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

Neutron Penetration depth : R. Pynn, "Neutron scattering: a primer." *Los Alamos Science* 19 (1990): 1-31.
APS X-ray penetration depth: C. Powell, personal communication.

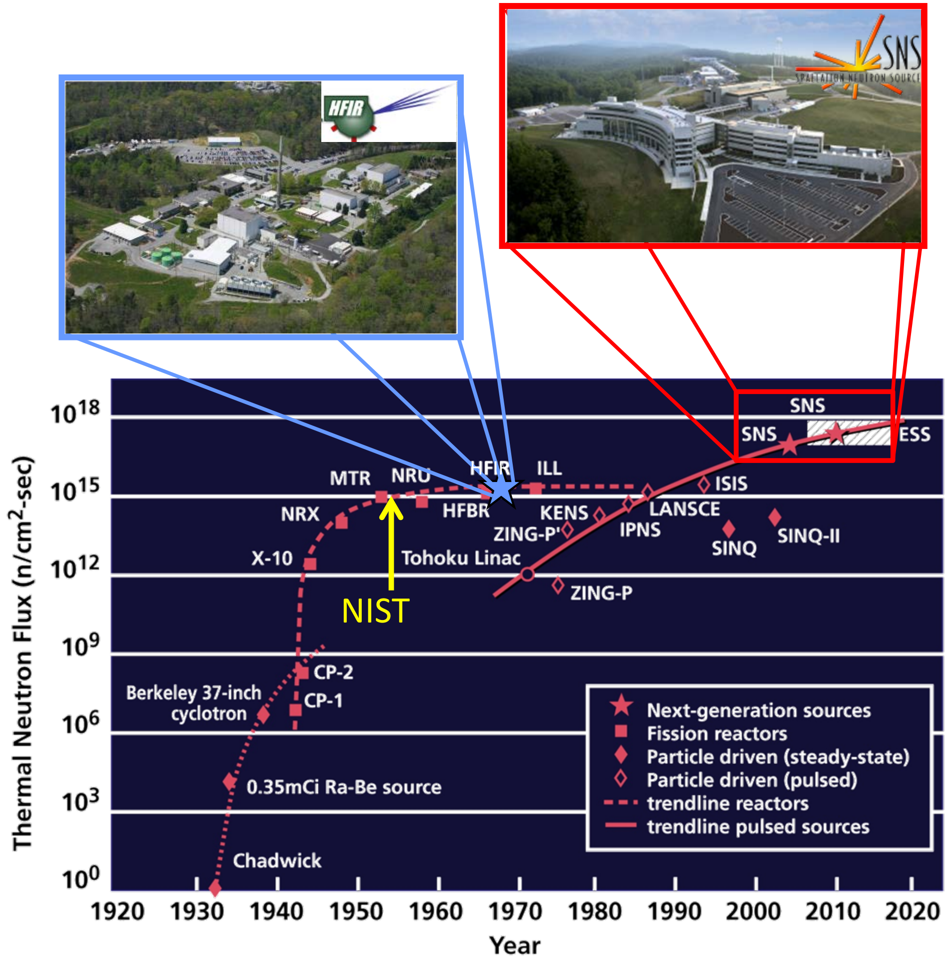
Neutrons at ORNL

High Flux Isotope Reactor (HFIR)

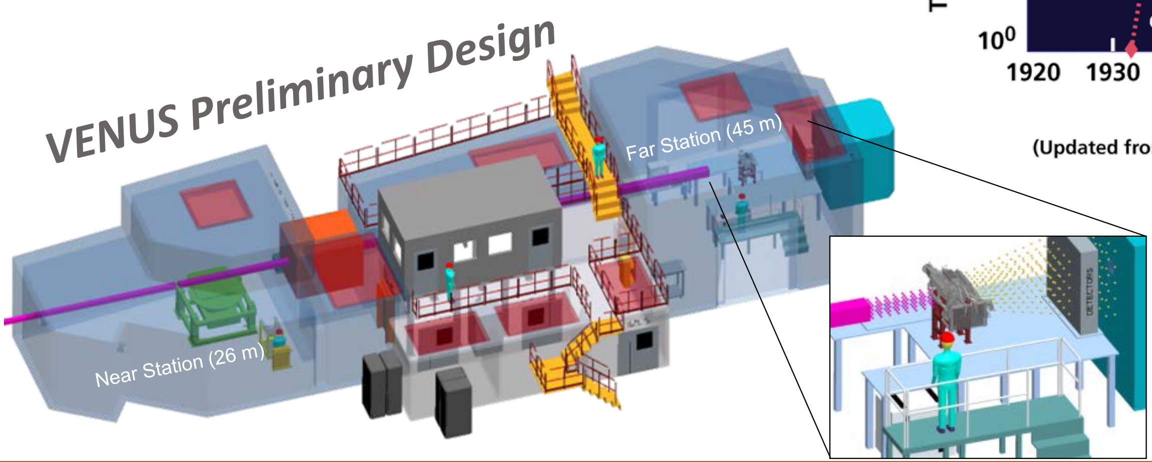
- Steady (i.e., non-pulsed) neutron source; “white” beam
- Imaging beam line accessible through user program

Spallation Neutron Source (SNS)

- Most intense pulsed neutron beam in the world; energy selective
- EERE promised $12M to VENUS imaging beamline; manufacturing
  - 39 months to build



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)



Estimated Beam Characteristics			
Resolution	20 µm	50 µm	200 µm
Max Field of View (cm x cm)	2 x 2	20 x 20	30x30

Stroboscopic technique images internal fluid with ~1 ms injection, 20 µs resolution

Sensor is Micro Channel Plate (MCP) detector, which allows very tight time bins

Injection timing for composite image:

- 0.4 - 1 ms injection with 20 µs resolution
- Targeting ~30 s of neutron exposure for each 20 µs frame
- Time-lapse imaging by aggregating stroboscopic sampling over ~10^6 injections

One 1 ms injection event

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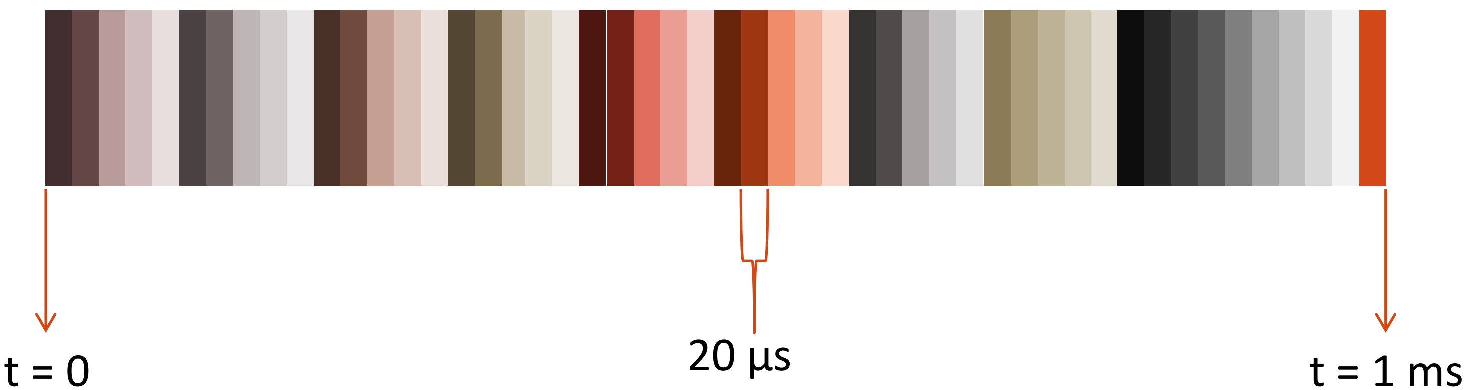

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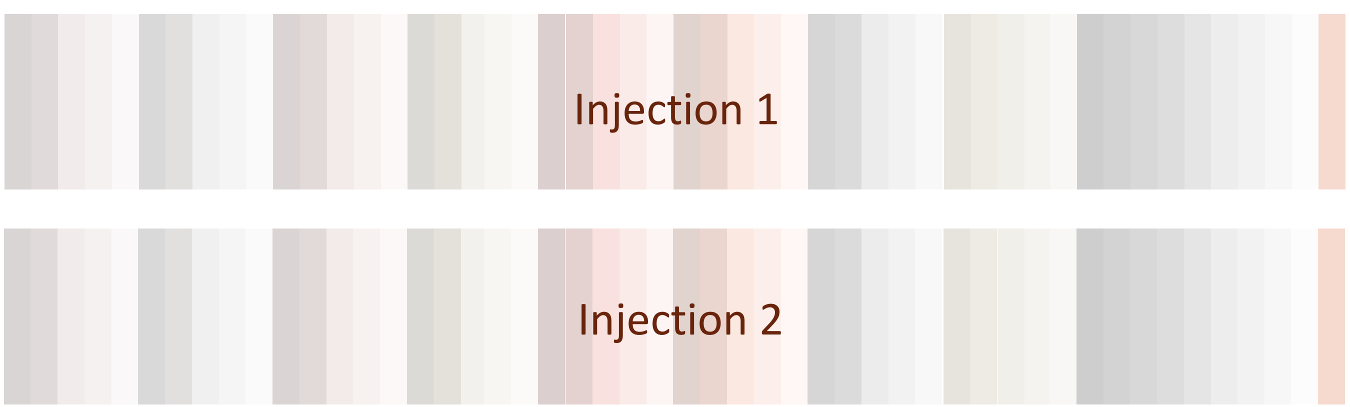

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